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# First muon anti-neutrino disappearance oscillation results from T2K

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This talk presented the first muon anti-neutrino disappearance analysis using data from the T2K anti-neutrino data taken in 2014 and up to March 12, 2015. The preliminary measured oscillation parameters, using  $2.3 \times 10^{20}$  protons on target, are  $\Delta\bar{m}_{32}^2 = 2.33_{-0.23}^{+0.27} \times 10^{-3} \text{ eV}^2$ , and  $\sin^2\bar{\theta}_{23} = 0.515_{-0.095}^{+0.085}$ . These oscillation parameters are consistent with the neutrino mode, and with the measurements of the MINOS experiment.

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<sup>1</sup>Work presented for the T2K collaboration.

# 1 Introduction

The Tokai to Kamioka (T2K) is a long baseline neutrino oscillation experiment situated in Japan[1]. The T2K experiment was built to measure the accelerator neutrino mixing angle  $\theta_{13}$ , to do precision measurements of the atmospheric neutrino mixing parameters  $\theta_{23}$  and  $\Delta m_{32}^2$ , and to search for a CP-violating phase,  $\delta_{CP}$  in the neutrino sector. Results of these measurements using a muon neutrino beam have been reported previously [2, 4, 5, 6, 7, 8, 9].

The T2K beam is a predominantly muon neutrino beam which is produced with a high intensity ( $\sim 330$  kW) 30 GeV proton beam striking a carbon target at the Japan Proton Accelerator Research Complex (J-PARC). The proton beam is measured with a series of beam monitors, including an Optical Transition Rate (OTR) monitor just upstream of the target[10]. The positive (negative) charged pions and kaons produced in this target are focused using a series of three magnetic horns. The positive (negative) charged mesons decay in a 100 m long decay volume producing muon (anti)neutrinos. Muons making it to the end of the 100 m long decay pipe are monitored with a Muon Monitor (MuMon)[11]. The electron neutrino contamination in the beam is only  $\sim 1\%$ [12][13].

The beam is measured 280 m from the target by an on-axis detector, INGRID[14], which monitors the beam direction, and by an off-axis detector, ND280. The tracker section of the magnetized off-axis detector is comprised of two active scintillator Fine Grained Detector (FGDs) which act as a neutrino targets[16], interleaved with three Time Projection Chambers to measure the momentum and type of charged particles produced in the neutrino interactions[15]. Upstream of the tracker is a detector designed to identify  $\pi^0$ s produced in neutrino interactions[17]. Surrounding the tracker and  $\pi^0$  detectors are electromagnetic calorimeters[18], and side muon range detectors between the magnet yokes[19].

The T2K far detector, Super-Kamiokande (SK), is 295 km from the production target, and, similar to ND280, it is off the beam axis by  $2.5^\circ$ . The off-axis beam is used to tune the energy around  $E \sim 0.6$  GeV in order to maximize the neutrino oscillations for the fixed  $L = 295$  km to the far detector. The overview of beam and detectors of the T2K experiment are shown in Fig. 1.

## 2 Oscillation analysis flow

In order to measure the neutrino oscillation parameters  $\theta_{23}$  and  $\Delta m_{32}^2$ , the number of  $\nu_\mu$  events in bins of reconstructed lepton momentum and angle is predicted using a detailed simulation.

Input to the number of events predicted comes from prior global measurements of the neutrino cross sections, measurement of the pion and kaon parents to the

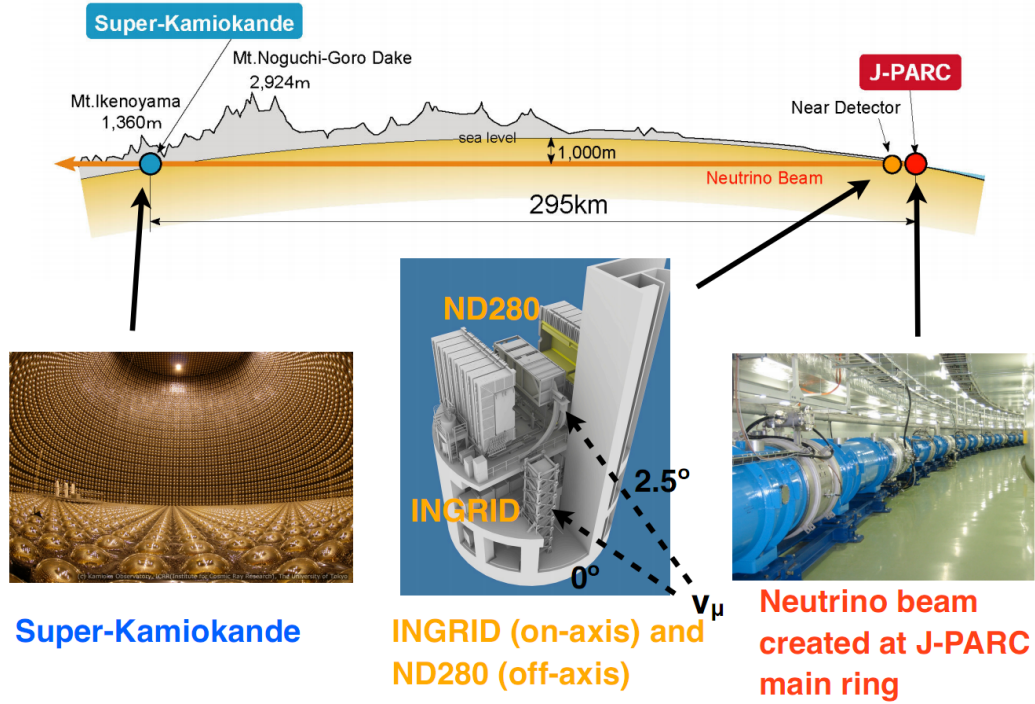


Figure 1: Overview of the T2K experiment (top), the T2K far detector (bottom-left), the near detectors at 280 m (bottom-middle), and the primary proton beamline (bottom-right).

neutrino production using data from the CERN NA61 experiment. This prediction is constrained by a fit to the T2K near detector data. For previous analyses of neutrino data, the near detector  $\nu_\mu$  interactions were broken into three samples, based on whether there was no pions, a single pion, or any other number of particles in the event[2]. For the anti-neutrino mode, the dataset is smaller, so the near detector data is only broken into single track and multi-track samples. The predicted flux of neutrinos is shown in the left panel of Fig. 2, and the predicted cross section is in the right panel[20]. A full covariance matrix of the anti-correlated uncertainties between the flux and cross section is used in the event rate prediction at the T2K far detector (Super Kamiokande).

The oscillation model is described by the Pontecorvo-Maki-Nakagata-Sakata (PMNS) matrix describing the neutrino flavour states ( $\nu_e, \nu_\mu, \nu_\tau$ ) as a quantum mechanical mixture of the neutrino mass states ( $\nu_1, \nu_2, \nu_3$ ). A full three flavour model, including a CP-violating phase is used, and includes matter effects. To first order, ignoring the CP violation and matter effects, the probability of a  $\nu_\mu$  of energy  $E$  remaining a  $\nu_\mu$  after travelling a distance  $L$  is:

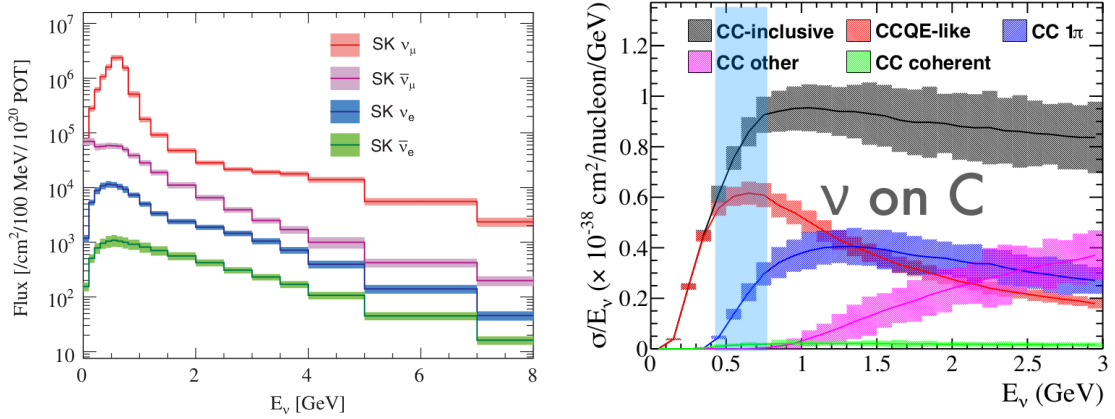


Figure 2: The predicted neutrino fluxes at the off-axis near detector, ND280, are shown in the left plot, and the neutrino cross sections on carbon, before near detector constraints, are shown in the right plot.

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(\Delta m_{32}^2 \frac{L}{4E}). \quad (1)$$

### 3 Neutrino oscillation results with anti-neutrinos

The muon neutrino event selection in the T2K far detector are events which are fully contained, have only one reconstructed Cherenkov ring, have a muon-like particle identification, have momentum greater than 200 MeV/c, and have one or fewer decay electrons. The predicted number of events in the far detector for this event selection is 19.9 with oscillation, and 58.9 without oscillation. The data, shown in the left panel of Fig. 3 has 17 candidate  $\bar{\nu}_\mu$  events, which clearly favours the oscillation model.

Three separate oscillation analyses were performed, two using frequentist methods, and the other using Bayesian methods. In all cases the fit was evaluated by maximizing a likelihood which is the product of a Poisson term and systematic uncertainty terms. In these fits all of the oscillation parameters were fixed to the PDG2014 and previous T2K neutrino-mode data values except for the oscillation parameters  $\bar{\theta}_{23}$  and  $\Delta\bar{m}_{32}^2$ . The atmospheric neutrino and anti-neutrino oscillation parameters are treated as independent while the other parameters are the same for neutrino and anti-neutrino.

The best fit for the oscillation parameters, using  $2.3 \times 10^{20}$  protons on target, are  $\Delta\bar{m}_{32}^2 = 2.33^{+0.27}_{-0.23} \times 10^{-3} \text{ eV}^2$ , and  $\sin^2\bar{\theta}_{23} = 0.515^{+0.085}_{-0.095}$ . These results include all of the systematic uncertainties, and is still dominated by the statistical uncertainty. More data is needed to reach the same level of precision already achieved with neutrino mode data. The results are consistent with the neutrino mode, as shown in the

right panel of Fig. 3. The event prediction with maximal mixing angle is clearly preferred over the no-oscillation hypothesis. These results provide a tighter constraint on the mixing angle than the previous MINOS results, and are consistent with those results[3].

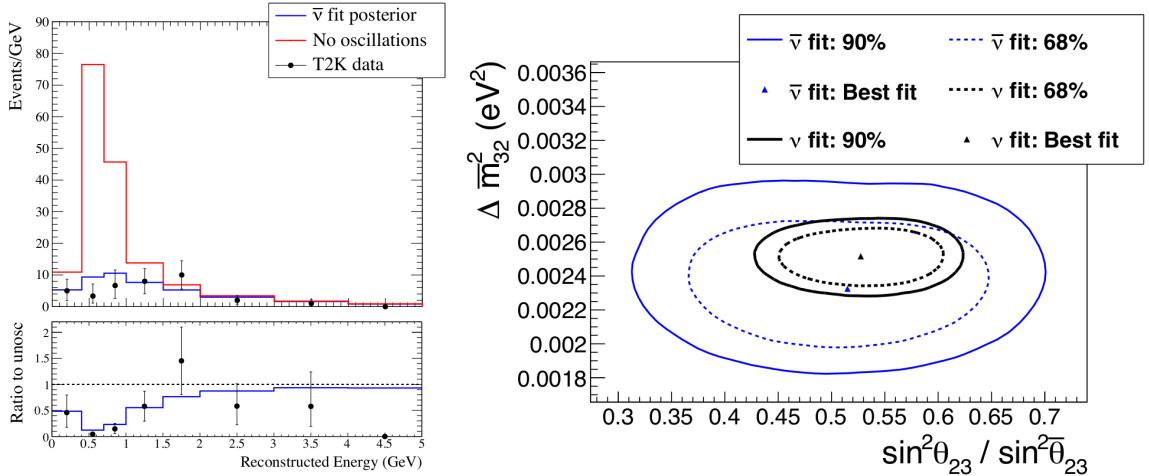


Figure 3: The  $\bar{\nu}_\mu$  data at the T2K far detector are shown in the left panels as points, and the predicted number of events is shown as the solid lines. The right panel shows an overlay of the best fit  $\Delta m_{32}^2$  and  $\sin^2 \theta_{23}$  with 68% and 90% contours for the anti-neutrino data (blue) and for the neutrino data (black).

## 4 Conclusion

Using the first anti-neutrino data from the T2K beam, we have shown that the  $\bar{\nu}_\mu$  disappearance oscillation is the same as for  $\nu_\mu$  within the current statistics. Results using the appearance channel are also being analyzed, and will be combined with the data presented here to put constraints on the CP violating phase ( $\delta_{CP}$ ). These further results have already been presented at conferences as these proceedings are being written.

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